

State-independent teleportation of an atomic state between two cavities

Shi-Biao Zheng

Department of Electronic Science and Applied Physics

Fuzhou University

Fuzhou 350002, P. R. China

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A scheme is presented for the teleportation of an unknown atomic state between two separated cavities. The scheme involves two interaction-detection cycles and uses resonantly coupled atoms with an additional ground state not coupled to the cavity field. Remarkably, the damping of one basis state is balanced by that of the other basis state and the state with photon loss in the first interaction-detection cycle is eliminated by the second cycle. Therefore, the fidelity of teleportation is independent of the teleported state and insensitive to the atomic spontaneous emission, cavity decay, and detection inefficiency, which is obviously in contrast to the original scheme by Bose et al. [Phys. Rev. Lett. 83 (1999) 5158].

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Quantum teleportation, first proposed by Bennett and colleagues in 1993 [1], is a means of transporting an unknown quantum state from one place to another without the requirement to move the particle which carries the quantum information. As quantum teleportation is one of basic methods of quantum communication [2] and may be useful in quantum computation [3], it has attracted considerable attention in recent years. Experimental realizations of quantum teleportation have been reported using optical systems with both discrete [4] and continuous variables [5], nuclear magnetic resonance [6], and trapped ions [7].

The cavity QED system with atoms interacting with quantized electromagnetic fields is almost an ideal candidate for implementing tasks of quantum information processing because atoms are suitable for storing information and photons suitable for transporting information. A number of cavity QED based schemes have been presented for teleportation of an unknown atomic state. Most of earlier schemes used atoms as the flying qubits to transfer quantum information [8]. Therefore, these schemes are not suitable for long-distance quantum teleportation. The proposal by Bose et al. [9], using atoms as the stationary qubits and photons as the flying qubits, is promising for quantum communication. The scheme is based on the detection of photons leaking out of single-mode cavities in which the atoms are trapped. Using more complex experimental setups related schemes for quantum teleportation [10-12] and entanglement engineering have also been presented [13-17].

In the scheme of Ref. [9], the final state of the second atom is a mixed state, which is different from the initial state of the first atom, and the fidelity depends on the teleported state. Furthermore, the fidelity is affected by cavity decay and imperfect photodetection. This is due to the fact that the two basis states are not equally damped and the state with two photons emitted is not eliminated. In this paper, we propose a scheme involving two interaction-detection cycles using resonantly coupled atoms with an additional ground state not coupled to the cavity field. In our scheme, the basis states are equally damped and the state with photon loss in the first interaction-detection cycle is eliminated by the second cycle. Therefore, the fidelity is state-independent and insensitive to cavity decay, atomic spontaneous emission, and detection inefficiency. Furthermore, our scheme uses resonant atom-cavity interaction, instead of Raman coupling used in Ref. [9], and thus the interaction time is greatly shortened, which is important for suppressing decoherence and improving the success probability. Our scheme allows high-fidelity teleportation of an unknown atomic state without using a more complex experimental setup.

The atoms have one excited state $|e\rangle$ and two ground states $|g\rangle$ and $|f\rangle$, as shown in Fig. 1. The quantum information is encoded in the ground states $|f\rangle$ and $|g\rangle$. The transition $|g\rangle \rightarrow |e\rangle$ is resonantly coupled to the cavity mode. The transition $|e\rangle \rightarrow |f\rangle$ is dipole-forbidden. The setup is shown in Fig. 2. Two distant atoms are trapped in two separate single-mode optical cavities, respectively. Photons leaking out of the cavities are mixed on a beam-splitter, which destroys which-path information. Then the photons are detected by two photodetectors. We here assume that the cavities are one sided so that the only photon leakage occurs through the sides of the cavities facing the beam-splitter.

The whole procedure of our scheme is composed of quantum information splitting and recombination. Each atom is first entangled with the corresponding cavity mode via resonant interaction. The detection of one photon leaking out of the cavities and passing through the beam-splitter corresponds to measurement of the joint state of the two cavities, which collapses the two distant atoms to an entangled state. After the first interaction-detection cycle, the quantum information initially encoded in atom 1 is shared by the two atoms. The process is referred to as entanglement swapping [18]. During the second interaction, if the atoms emit one photon the quantum state of atom 1 is transferred to the cavity fields. The detection of the photon enables the splitted quantum information to be

recombined and completely encoded in atom 2 [19].

Assume that the atom (atom 1), whose state is to be teleported, is initially in the state

$$|\phi_1\rangle = c_f |f_1\rangle + c_g |g_1\rangle, \quad (1)$$

where c_f and c_g are unknown coefficients. Both the two cavities are initially in the vacuum state $|0\rangle$. The first step is the transfer of one photon to the cavity through a half-cycle of the vacuum Rabi-oscillation of the atom-cavity system. The vacuum Rabi half-cycle is initiated by exciting the state $|g_1\rangle$ to $|e_1\rangle$. This leads to

$$|\phi'_1\rangle = c_f |f_1\rangle + c_g |e_1\rangle. \quad (2)$$

The emission or non-emission of a photon depends on whether the initial state is $|g_1\rangle$ or $|f_1\rangle$, providing the essential tool for generating entanglement between the atom and cavity field. This is distinguished with the scheme of Ref. [9], in which two ground atomic states are coupled to the cavity field via Raman process and atom 1 is disentangled with the cavity field after the atom-cavity interaction. The atom (atom 2), to receive the teleported state, is initially prepared in the state

$$|\phi_2\rangle = \frac{1}{\sqrt{2}}(|e_2\rangle + |f_2\rangle). \quad (3)$$

In Ref. [9], atom 2 is initially in a ground state and the entanglement between atom 2 and cavity 2 is obtained after a Rabi quater-cycle, which is obviously in contrast with the present case. The aim of using the initial state $|\phi_2\rangle$ is to let the basis states $|g_1\rangle |f_2\rangle$ and $|f_1\rangle |g_2\rangle$ be equally damped, as shown below. This allows the effect of decoherence in cavity 1 is balanced by that in cavity 2.

In the interaction picture, the Hamiltonian in each cavity is

$$H_j = g(a_j S_j^+ + a_j^\dagger S_j^-), \quad (4)$$

where $S_j^+ = |e_j\rangle \langle g_j|$ and $S_j^- = |g_j\rangle \langle e_j|$ are the raising and lowering operators of the j th ($j=1,2$) atom, a_j and a_j^\dagger are the annihilation and creation operators of the j th cavity mode, and g is the atom-cavity coupling strength. The Hamiltonian of Eq. (4) does not include the effects of the atomic spontaneous emission and cavity decay. Under the condition that no photon is detected either by the atomic spontaneous emission or by the leakage through the cavity mirror, the evolution of the system is governed by the conditional Hamiltonian

$$H_{con,j} = H_j - i\frac{\kappa}{2}a_j^\dagger a_j - i\frac{\Gamma}{2}|e_j\rangle \langle e_j|, \quad (5)$$

where κ is the cavity decay rate and Γ is the atomic spontaneous emission rate. The time evolution for the state $|e_j\rangle |0_j\rangle$ is

$$|e_j\rangle |0_j\rangle \rightarrow e^{-(\kappa+\Gamma)t/4} \left\{ [\cos(\beta t) + \frac{\kappa - \Gamma}{4\beta} \sin(\beta t)] |e_j\rangle |0_j\rangle - i\frac{g}{\beta} \sin(\beta t) |g_j\rangle |1_j\rangle \right\}, \quad (6)$$

where

$$\beta = \sqrt{g^2 - (\kappa - \Gamma)^2/16}. \quad (7)$$

After an interaction time t_1 given by $\tan(\beta t_1) = 4\beta/(\Gamma - \kappa)$, the whole system evolves to

$$\begin{aligned} |\psi_1\rangle = & \frac{1}{\sqrt{2}} \{ c_f |f_1\rangle |0_1\rangle - i c_g \frac{g}{\beta} e^{-(\kappa+\Gamma)t_1/4} \sin(\beta t_1) |g_1\rangle |1_1\rangle \} \\ & \{ |f_2\rangle |0_2\rangle - i \frac{g}{\beta} e^{-(\kappa+\Gamma)t_1/4} \sin(\beta t_1) |g_2\rangle |1_2\rangle \}. \end{aligned} \quad (8)$$

Unlike the scheme of Ref. [9], the state of atom 1 is not transferred to cavity 1, and atom 2 and cavity 2 are not prepared in a maximally entangled state.

Now we perform the transformation:

$$|f_j\rangle \rightarrow |g_j\rangle; |g_j\rangle \rightarrow -|f_j\rangle. \quad (9)$$

This leads to

$$|\psi_2\rangle = \frac{1}{\sqrt{2}}\{c_f |g_1\rangle |0_1\rangle + ic_g \frac{g}{\beta} e^{-(\kappa+\Gamma)t_1/4} \sin(\beta t_1) |f_1\rangle |1_1\rangle\} \\ \{ |g_2\rangle |0_2\rangle + i \frac{g}{\beta} e^{-(\kappa+\Gamma)t_1/4} \sin(\beta t_1) |f_2\rangle |1_2\rangle\}. \quad (10)$$

After the transformation the atom-cavity interaction is frozen since $H_j |\psi_2\rangle = 0$. Now we wait for the photodetectors to click. The registering of a click at one of the photodetectors corresponds to the action of the jump operators $(a_1 \pm a_2)/\sqrt{2}$ on the state $|\psi_2\rangle$, where "+" corresponds to the detection of the photon at the photodetector D_+ , while "-" corresponds to the detection of the photon at D_- . The system is then projected to

$$|\psi_3\rangle = ic_g \frac{g}{2\beta} e^{-(\kappa+\Gamma)t_1/4 - \kappa\tau_1/2} \sin(\beta t_1) |f_1\rangle |0_1\rangle |g_2\rangle |0_2\rangle \\ \pm ic_f \frac{g}{2\beta} e^{-(\kappa+\Gamma)t_1/4 - \kappa\tau_1/2} \sin(\beta t_1) |g_1\rangle |0_1\rangle |f_2\rangle |0_2\rangle \\ - c_g \frac{g^2}{2\beta^2} e^{-(\kappa+\Gamma)t_1/2 - \kappa\tau_1} \sin^2(\beta t_1) |f_1\rangle |f_2\rangle (|0_1\rangle |1_2\rangle \pm |1_1\rangle |0_2\rangle), \quad (11)$$

where τ_1 is the waiting time. In comparison with the scheme of Ref. [9], after the detection of the photon atom 1 is entangled with atom 2 and the cavity modes, and the two basis states $|f_1\rangle |g_2\rangle$ and $|g_1\rangle |f_2\rangle$ are equally damped. Then we wait for another time τ_2 . Suppose that no photon is detected during this period. Due to the cavity decay the system evolves to

$$|\psi_4\rangle = ic_g \frac{g}{2\beta} e^{-(\kappa+\Gamma)t_1/4 - \kappa\tau_1/2} \sin(\beta t_1) |f_1\rangle |0_1\rangle |g_2\rangle |0_2\rangle \\ \pm ic_f \frac{g}{2\beta} e^{-(\kappa+\Gamma)t_1/4 - \kappa\tau_1/2} \sin(\beta t_1) c_f |g_1\rangle |0_1\rangle |f_2\rangle |0_2\rangle \\ - c_g \frac{g^2}{2\beta^2} e^{-(\kappa+\Gamma)t_1/2 - \kappa(\tau_1 + \tau_2/2)} \sin^2(\beta t_1) |f_1\rangle |f_2\rangle (|0_1\rangle |1_2\rangle \pm |1_1\rangle |0_2\rangle). \quad (12)$$

If τ_2 is long enough so that $e^{-\kappa\tau_2/2} \ll 1$ the last term of $|\psi_4\rangle$ can be discarded. This leads to

$$|\psi_4\rangle = i \frac{g}{2\beta} e^{-(\kappa+\Gamma)t_1/4 - \kappa\tau_1/2} \sin(\beta t_1) (c_g |f_1\rangle |0_1\rangle |g_2\rangle |0_2\rangle \pm c_f |g_1\rangle |0_1\rangle |f_2\rangle |0_2\rangle). \quad (13)$$

Then we sequentially perform the following transformations on atom 1: $|g_1\rangle \rightarrow |e_1\rangle$ and $|f_1\rangle \rightarrow |g_1\rangle$. Meanwhile we excite the state $|g_2\rangle$ to $|e_2\rangle$. This leads to

$$|\psi_5\rangle = i \frac{g}{2\beta} e^{-(\kappa+\Gamma)t_1/4 - \kappa\tau_1/2} \sin(\beta t_1) (c_g |g_1\rangle |0_1\rangle |e_2\rangle |0_2\rangle \pm c_f |e_1\rangle |0_1\rangle |f_2\rangle |0_2\rangle). \quad (14)$$

Due to the transformations each atom interacts with the corresponding cavity mode again. Suppose that no photon is detected during the interaction the evolution of the system is

$$|\psi_6\rangle = ic_g \frac{g}{2\beta} e^{-(\kappa+\Gamma)(t_1+t_2)/4 - \kappa\tau_1/2} \sin(\beta t_1) |g_1\rangle |0_1\rangle \{ [\cos(\beta t_2) \\ + \frac{\kappa - \Gamma}{4\beta} \sin(\beta t_2)] |e_2\rangle |0_2\rangle - i \frac{g}{\beta} \sin(\beta t_2) |g_2\rangle |1_2\rangle \} \\ \pm ic_f \frac{g}{2\beta} e^{-(\kappa+\Gamma)(t_1+t_2)/4 - \kappa\tau_1/2} \sin(\beta t_1) \{ [\cos(\beta t_2) \\ + \frac{\kappa - \Gamma}{4\beta} \sin(\beta t_2)] |e_1\rangle |0_1\rangle - i \frac{g}{\beta} \sin(\beta t_2) |g_1\rangle |1_1\rangle \} |f_2\rangle |0_2\rangle, \quad (15)$$

where t_2 is the interaction time. The registering of a click at one of the photodetectors at some moment projects atom 2 to

$$|\varphi\rangle = c_g |g_2\rangle \pm c_f |f_2\rangle, \quad (16)$$

with atom 1 left in the state $|g_1\rangle$ and the two cavity modes left in the vacuum state $|0_1\rangle |0_2\rangle$. Here "+" corresponds to the detection of two photons at the same photodetector during the two interaction-detection cycles, while "-"

corresponds to the detection of the photons at different photodetectors. If the two photons are detected in the same photodetector atom 2 is just in the initial state of atom 1. If the two photons are detected at different photodetectors we perform the rotation $|f_2\rangle \rightarrow -|f_2\rangle$ to reconstruct the initial state of atom 1.

If one wishes to wait a time t_d during the second stage, the probability of success is

$$P = \frac{1}{2}e^{-(\kappa+\Gamma)t_1/2}\{1 - e^{-(\kappa+\Gamma)t_d/2}[\cos^2(\beta t_d) + \frac{(\kappa - \Gamma)^2 + 4g^2}{4\beta^2}\sin^2(\beta t_d) + \frac{\kappa - \Gamma}{4\beta}\sin(2\beta t_d)]\}. \quad (17)$$

If t_d is long enough so that $e^{-(\kappa+\Gamma)t_d/2} \ll 1$ the success probability is $P = e^{-(\kappa+\Gamma)t_1/2}/2$. The success probability increases as the needed interaction time t_1 decreases.

Due to the imperfection of the photodetectors, there is a probability that two photons have leaked out of the cavities but only one photon is detected during the first interaction-detection cycle, which leads to the state $|f_1\rangle|f_2\rangle|0_1\rangle|0_2\rangle$. In this case no photon is emitted during the second cycle and the event is discarded. The scheme is conditional upon the detection of two emitted photons. If one of the emissions is not detected, the scheme fails and the procedure restarts. Therefore, the imperfection of the photodetectors does not affect the fidelity of the teleported state. Set the detection efficiency to be η . Then the success probability is $P' = \eta^2 P$.

Because of imperfect timing of the interaction time t_1 , atom 2 is finally in the mixed state

$$\rho = (|\varepsilon_1|^2 + 2|\varepsilon_{2,\pm}|^2 + 2|\varepsilon_{3,\pm}|^2)^{-1}[(|\varepsilon_1|^2 + |\varepsilon_{2,\pm}|^2)|\varphi'\rangle\langle\varphi'| + (|\varepsilon_{2,\pm}|^2 + 2|\varepsilon_{3,\pm}|^2)|g_2\rangle\langle g_2|], \quad (18)$$

where

$$|\varphi'\rangle = (|\varepsilon_1|^2 + |\varepsilon_{2,\pm}|^2)^{-1/2}[\varepsilon_1(\pm c_g|g_2\rangle \pm c_f|f_2\rangle) + \varepsilon_{2,\pm}|e_2\rangle], \quad (19)$$

and

$$\begin{aligned} \varepsilon_1 &= BEe^{-\kappa\tau_1/2}, \\ \varepsilon_{2,\pm} &= (c_g \pm c_f)ACDE, \\ \varepsilon_{3,\pm} &= (c_g \pm c_f)ACE^2, \\ A &= e^{-(\kappa+\Gamma)(t_1+\delta t_1)/4}\{[\cos[\beta(t_1 + \delta t_1)] + \frac{\kappa - \Gamma}{4\beta}\sin[\beta(t_1 + \delta t_1)]]\}, \\ B &= i\frac{g}{\beta}e^{-(\kappa+\Gamma)(t_1+\delta t_1)/4}\sin[\beta(t_1 + \delta t_1)], \\ C &= -i\frac{g}{\beta}e^{-(\kappa+\Gamma)\tau_1/4}\sin(\beta\tau_1), \\ D &= e^{-(\kappa+\Gamma)t_2/4}[\cos(\beta t_2) + \frac{\kappa - \Gamma}{4\beta}\sin(\beta t_2)], \\ E &= -i\frac{g}{\beta}e^{-(\kappa+\Gamma)t_2/4}\sin(\beta t_2). \end{aligned} \quad (20)$$

Here δt_1 is the deviation from the desired interaction time. With imperfect timing of the interaction time t_1 being considered, the fidelity is

$$F = \frac{|\varepsilon_1|^2 + (|\varepsilon_{2,\pm}|^2 + 2|\varepsilon_{3,\pm}|^2)|c_g|^2}{|\varepsilon_1|^2 + 2|\varepsilon_{2,\pm}|^2 + 2|\varepsilon_{3,\pm}|^2}. \quad (21)$$

When the timing is not perfect the fidelity depends on the state to be teleported.

In order to perform the transformation in Eq. (11) we use a pair of off-resonant classical fields with the same Rabi frequency Ω to drive the transitions $|g_j\rangle \rightarrow |h_j\rangle$ and $|f_j\rangle \rightarrow |h_j\rangle$, where $|h_j\rangle$ is an auxiliary excited state. The two classical fields are detuned from the respective transitions by the same amount δ . In the case that the detuning δ is much larger than the Rabi frequency Ω the upper level $|h_j\rangle$ can be adiabatically eliminated and the two classical fields just induce the Raman transition between the states $|g_j\rangle$ and $|f_j\rangle$ [20]. The Raman coupling strength is $\lambda = \Omega^2/\delta$. The time needed to perform the required transformation is $\pi/2\lambda$. Under the condition $\lambda \gg g$, the atom-cavity

interaction can be neglected during this transformation. Set $\Omega = 3 \times 10^2 g$ and $\delta = 10\Omega$. During this transformation the probability that each atom exchanges an excitation with the cavity mode is on the order of $(g\pi/2\lambda)^2 \simeq 2.74 \times 10^{-3}$.

The required atomic level configuration can be achieved in Cs. The hyperfine levels $|F=4, m=-1\rangle$ and $|F=4, m=0\rangle$ of $6S_{1/2}$ can act as the ground states $|g\rangle$ and $|f\rangle$, respectively, while the hyperfine levels $|F'=5, m'=0\rangle$ and $|F'=5, m'=-1\rangle$ of $5^2P_{3/2}$ can act as the excited states $|e\rangle$ and $|h\rangle$, respectively. In a recent cavity QED experiment with Cs atoms trapped in an optical cavity, the corresponding atom-cavity coupling strength is $g = 2\pi \times 34 MHz$ [21]. The decay rates for the atomic excited states and the cavity mode are $\Gamma = 2\pi \times 2.6 MHz$ and $\kappa = 2\pi \times 4.1 MHz$, respectively. The required interaction time t_1 is about $7.4 \times 10^{-3} \mu s$. The waiting times τ_1 and τ_2 are on the order of $2/\kappa \simeq 7.8 \times 10^{-2} \mu s$ and $20/\kappa \simeq 7.8 \times 10^{-1} \mu s$, respectively. The waiting time t_d during the second stage is on the order of $20/(\kappa + \Gamma) \simeq 4.8 \times 10^{-1} \mu s$. The total time needed to complete the teleportation is on the order of $1.35 \mu s$. Set $c_f = c_g = \frac{1}{\sqrt{2}}$, $\delta t_1 = 0.05 t_1$, and $\eta = 0.6$ [9]. Then the success probability and fidelity are about 0.15 and 0.998, respectively. The present scheme works in the Lamb-Dicke regime, i.e., the spatial extension of the atomic wave function should be much smaller than the wavelength of the light fields. In a recent experiment [22], the localization to the Lamb-dicke limit of the axial motion was demonstrated for a single atom trapped in an optical cavity.

In summary, we have proposed a scheme for long-distance teleportation of the state of an atom trapped in an optical cavity to a second atom trapped in another distant optical cavity. The scheme involves two interaction-detection cycles and uses resonant atoms with an additional ground state not coupled to the cavity field. The distinct advantage of our scheme is that the teleportation fidelity is state-independent and insensitive to decoherence and imperfect photodetection in principle.

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- [1] C. H. Bennett et al., Phys. Rev. Lett. 70, 1895 (1993).
 - [2] H. J. Briegel et al., Phys. Rev. Lett. 81, 5932 (1998).
 - [3] D. Gottesman and I. L. Chuang, Nature 402, 390 (1999).
 - [4] D. Bouwmeester et al., Nature (London) 390, 575 (1997); D. Boschi et al., Phys. Rev. Lett. 80, 1121 (1998).
 - [5] A. Furusawa et al., Science 282, 706 (1998).
 - [6] M. A. Nielsen et al., Nature 396, 52 (1998).
 - [7] M. Riebe et al., Nature 429, 734 (2004); M. D. Barrett et al., Nature 429, 737 (2004).
 - [8] L. Davidovich et al., Phys. Rev. A50, R895 (1994); J. I. Cirac and A. S. Parkins, Phys. Rev. A50, R4441 (1994); M. H. Y. Moussa, Phys. Rev. A 54, 4661 (1996); S. B. Zheng and G. C. Guo, Phys. Lett. A 232, 171 (1997).
 - [9] S. Bose et al., Phys. Rev. Lett. 83, 5158 (1999).
 - [10] J. Cho and W-W. Lee, Phys. Rev. A 70, 034305 (2004).
 - [11] B. Yu et al., Phys. Rev. A 70, 014302 (2004).
 - [12] S. B. Zheng and G. C. Guo, Phys. Rev. A 73, 032329 (2006).
 - [13] C. Cabrillo, Phys. Rev. A 59, 1025 (1999).
 - [14] X. Feng et al., Phys. Rev. Lett. 90, 217902 (2003).
 - [15] L. M. Duan and H. J. Kimble, Phys. Rev. Lett. 90, 253601 (2003).
 - [16] D. E. Browne, M. B. Plenio, and S. F. Huelga, Phys. Rev. Lett. 91, 067901 (2003).
 - [17] S. D. Barrett and P. Kok P, Phys. Rev. A 71, 060310 (2005).
 - [18] M. Zukowski, A. Zeilinger, M. A. Horne, and A. K. Ekert, Phys. Rev. Lett. 71, 4287 (1993).
 - [19] M. Hillery, V. Bužek, and A. Berthiaume, Phys. Rev. A59, 1829 (1999).
 - [20] C. Monroe et al., Science 272, 1131 (1996).
 - [21] A. Boca, R. Miller, K. M. Birnbaum, A. D. Boozer, J. McKeever, and H. J. Kimble, quant-ph/0410164.
 - [22] A. D. Boozer, A. Boca, R. Miller, T. E. Northup, and H. J. Kimble, quant-ph/0606104.

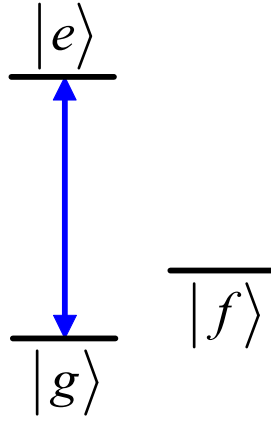


FIG. 1: The level configuration of the atoms. The transition $|g\rangle \rightarrow |e\rangle$ is resonantly coupled to the cavity mode and the additional ground state $|f\rangle$ is not coupled to the cavity mode.

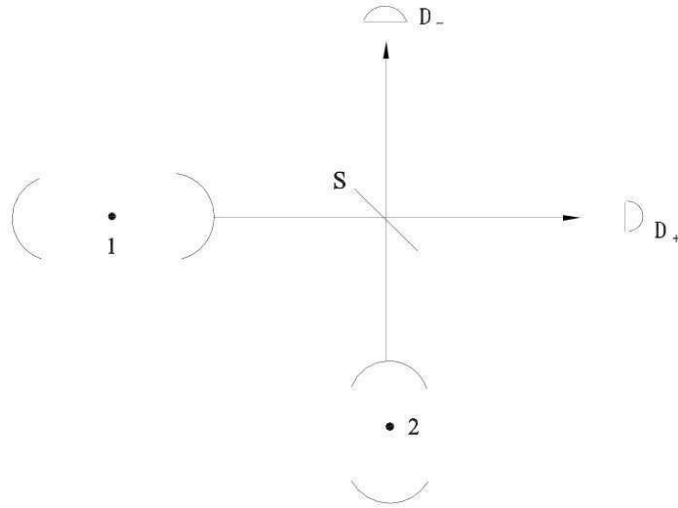


FIG. 2: The experimental setup. Two distant atoms are trapped in separate cavities. Photons leak through the sides of the cavities facing the beam-splitter S and then are detected by the photodetectors D_+ and D_- .